

Photoproduction Constraints on J/ψ -Nucleon Interactions

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Abstract:

Using J/ψ and open charm photoproduction data, we apply the vector meson dominance model to obtain constraints on the energy dependence of the inelastic J/ψ -nucleon cross section. Predictions of short distance QCD are in accord with these constraints, while recently proposed hadronic models for J/ψ dissociation strongly violate them.

The energy dependence of the inelastic J/ψ -nucleon cross section $\sigma_{\psi N}^{in}(s)$ is of great importance in understanding J/ψ suppression as signature for colour deconfinement in high energy nuclear collisions [1]. Calculations based on short distance QCD predict a strong threshold damping of $\sigma_{\psi N}^{in}(s)$, due to the suppression of high momentum gluons by the gluon distribution function in nucleons [2]-[5]; this damping persists also when finite target mass corrections are taken into account [6]. In contrast to such QCD studies, several recently proposed models based on hadron exchange suggest large threshold values of $\sigma_{\psi N}^{in}(s)$ [7] - [9]. The aim of this note is to show that available J/ψ and open charm photoproduction data can do much to clarify the situation.

The existing empirical information on J/ψ -hadron interactions comes from photoproduction and the vector meson dominance model (VMD) [10], which relates $e^+e^- \rightarrow \psi$, $\gamma N \rightarrow \psi N$ and $\psi - N$ data [11]. It is based on the assumption that fluctuations of the photon into quark-antiquark pairs are dominated by the corresponding hadronic resonances. As a result, the diffractive J/ψ -photoproduction cross section is related to elastic $\psi - N$ scattering,

$$\sigma(\gamma N \rightarrow \psi N) = \left(\frac{4\pi\alpha}{\gamma_\psi^2} \right) \sigma_{el}^{\psi N}. \quad (1)$$

Here γ_ψ is determined by the J/ψ -decay into e^+e^- ,

$$\Gamma(e^+e^- \rightarrow \psi) = \frac{\alpha^2}{3} \left(\frac{4\pi}{\gamma_\psi^2} \right) M_\psi, \quad (2)$$

with $\Gamma(e^+e^- \rightarrow \psi) = 5.26 \pm 0.37$ keV [15]. Furthermore, the optical theorem leads to

$$\left(\frac{d\sigma(\gamma N \rightarrow \psi N)}{dt} \right)_{t=0} = \frac{(1 + \rho^2)}{16\pi} \left(\frac{4\pi\alpha}{\gamma_\psi^2} \right) (\sigma_{tot}^{\psi N})^2, \quad (3)$$

where $\rho = [\text{Re } M(s)/\text{Im } M(s)]$ is the ratio of real to imaginary part of the ψ - N forward scattering amplitude. This vanishes at high energy, so that then Eq. (3) relates the total ψ - N cross section to forward J/ψ -photoproduction.

The first experimental measurements of the J/ψ -photoproduction cross section had already shown it to be very small compared to the corresponding cross sections for conventional vector mesons ρ, ω and ϕ [12]. One of the first explanations of this result had invoked the smallness of the Pomeranchuk pole residue for the J/ψ , i.e., the total cross section of ψ - N -interaction should be small, and the interaction of π and J/ψ was argued to be quite weak [13, 14]. Moreover, it was concluded there the J/ψ interaction with hadrons should be dominated by charmed particle production.

Today there exist quite good data. For c.m.s. energy $\sqrt{s} \simeq 20$ GeV (corresponding to a photon energy of about 200 GeV), the forward photoproduction cross section is about 100 nb/GeV² [11]. Assuming that here $\rho \simeq 0$, and using the quoted value for $\Gamma(e^+e^- \rightarrow \psi)$, we get $\sigma_{\text{tot}}^{\psi N} \simeq 1.7$ mb. Geometric arguments, which also assume $\rho = 0$, predict $\sigma_{\text{tot}}^{\psi N}/\sigma_{\text{tot}}^{NN} \simeq (r_\psi/r_N)^2$ [16]. With $r_\psi \simeq 0.2$ fm, $r_N \simeq 0.85$ fm and $\sigma_{\text{tot}}(NN) \simeq 40$ mb, this gives $\sigma_{\text{tot}}^{\psi N} \simeq 2.2$ mb. Thus both VDM and geometric considerations lead to a total high energy ψ - N cross section around 2 mb.

At $\sqrt{s} \simeq 20$ GeV, $\sigma(\gamma N \rightarrow \psi N) \simeq 17.5$ nb [11]; using Eq. (1), we obtain

$$\sigma_{\text{el}}^{\psi N} \simeq 25 \mu\text{b} \quad (4)$$

for the elastic ψ - N cross section at this energy. Hence the high energy ratio of elastic to total ψ - N cross sections is with

$$\frac{\sigma_{\text{el}}^{\psi N}}{\sigma_{\text{tot}}^{\psi N}} \simeq \frac{1}{70} \quad (5)$$

very much smaller than that for the interaction of light hadrons; the corresponding π - N ratio is an order of magnitude larger. At high energy, the total ψ - N cross section is thus strongly dominated by inelastic channels; for the J/ψ , it is apparently much more difficult to survive high energy interactions than it is for hadrons consisting of light quarks, so that most of $\sigma_{\text{tot}}^{\psi N}$ consists of open charm production. This is in accord with the Okubo-Zweig-Iizuka (OZI) rules, which forbid the J/ψ as $c\bar{c}$ bound state to annihilate into ordinary light hadrons and hence lead to charmed meson production. Such behaviour is also a natural consequence of partonic interactions, rather than black disc absorption.

Since Eq. (3) determines the total cross section only modulo $(1 + \rho^2)^{1/2}$, additional information is needed to determine $\sigma_{\text{in}}^{\psi N}(s)$. This is provided by the photoproduction of open charm, which we denote by $\sigma(\gamma N \rightarrow c\bar{c})$; it is empirically obtained by measuring D and D^* production. From VMD, we expect

$$\sigma(\gamma N \rightarrow c\bar{c}) \simeq \left(\frac{4\pi\alpha}{\gamma_\psi^2} \right) \sigma_{\text{in}}^{\psi N}. \quad (6)$$

Before applying this relation, the role of other vector mesons must be clarified. Intermediate light quark states, such as ρ or ω , could also produce open charm. Data on the cross section for open charm hadroproduction, in accord with perturbative calculations [17], give some 10 - 20 μb at $\sqrt{s} \simeq 20$ GeV. This is to be compared to $\sigma_{\text{tot}}^{\psi N} \simeq 2$ mb at the corresponding energy, keeping in mind the ratio of the photon couplings $\gamma_\rho^{-2}/\gamma_\psi^{-2} \simeq 5.18$.

Light vector mesons therefore contribute to open charm photoproduction at most on a 5 % level.

Further contributions could come from higher $c\bar{c}$ resonances, such as the ψ' . These are in fact also negligible, but for a different reason. VMD implicitly assumes that the fluctuations of a real photon into a $q\bar{q}$ pair are comparable in size to the relevant vector mesons. For light quarks and light mesons, this is the case, since both are of typical hadronic scale. For $\gamma \rightarrow c\bar{c}$, the scale is very much smaller, but it is also correspondingly smaller for the J/ψ , with both around 0.1 - 0.2 fm; hence VMD still makes sense. The higher $c\bar{c}$ vector mesons are much larger than the $c\bar{c}$ fluctuation, however, and so for them VMD ‘fails’ [14, 18]. This can be checked by considering the ratio of ‘elastic’ J/ψ to ψ' photoproduction. From VMD and the optical theorem, one expects

$$\frac{\sigma(\gamma N \rightarrow \psi' N)}{\sigma(\gamma N \rightarrow \psi N)} = \left(\frac{M_\psi}{M_{\psi'}} \right) \left(\frac{\Gamma(e^+e^- \rightarrow \psi')}{\Gamma(e^+e^- \rightarrow \psi)} \right) \left(\frac{\sigma_{\text{tot}}^{\psi' N}}{\sigma_{\text{tot}}^{\psi N}} \right)^2. \quad (7)$$

Geometric arguments [16] suggest $\sigma_{\text{tot}}^{\psi' N}/\sigma_{\text{tot}}^{\psi N} \simeq 4$, since the radius of the $2S$ state is more than twice that of the $1S$. Inserting the corresponding masses and decay widths, the ratio $\sigma(\gamma N \rightarrow \psi' N)/\sigma(\gamma N \rightarrow \psi N)$ is predicted to be 5.5. Photoproduction data [19], in contrast, give a ratio of 0.15 ± 0.03 , more than a factor 30 smaller. Evidently the ψ' can therefore also be neglected as an intermediate state in open charm photoproduction.¹

As a final consistency check, we can see if the $\sigma_{\text{in}}^{\psi N}$ determined by Eq. (6) from open charm photoproduction indeed converges at high energies to the $\sigma_{\text{tot}}^{\psi N}$ obtained from forward J/ψ photoproduction by Eq. (3). It will be found shortly that this is indeed the case.

We thus use the data for open charm photoproduction [20, 21] and Eq. (6) to determine the energy dependence of $\sigma_{\text{in}}^{\psi N}(s)$, while J/ψ photoproduction [11] and Eq. (1) gives that of $\sigma_{\text{el}}^{\psi N}(s)$. The results are shown in Fig. 1, together with the data for $(1+\rho^2)^{1/2}\sigma_{\text{tot}}^{\psi N}(s)$ as obtained from forward J/ψ photoproduction through VMD and the optical theorem (Eq. (3)). We note that at high energy, where we expect $\rho \rightarrow 0$, $\sigma_{\text{in}}^{\psi N}(s)$ indeed approaches $\sigma_{\text{tot}}^{\psi N}(s)$, so that the consistency check just mentioned is satisfied. The curves shown in Fig. 1 are χ^2 fits to the corresponding data, based on the functional form

$$\sigma_x^{\psi N}(s) = A_x \left\{ 1 - \left(\frac{s_0^x}{s} \right)^{1/2} \right\}^{k_x}, \quad (8)$$

where x refers to elastic and inelastic, respectively, and s_0^x denotes the corresponding threshold energy in each case. The parameters obtained are given in Table 1.

Dividing the data for $(1+\rho^2)^{1/2}\sigma_{\text{tot}}^{\psi N}(s)$ by the fitted forms $\sigma_{\text{in}}^{\psi N}(s) + \sigma_{\text{el}}^{\psi N}(s)$, we obtain the energy dependence of the ratio of real to imaginary parts of the $\psi - N$ scattering amplitude. This is shown in Fig. 2, together with a polynomial fit. We see that the conditions for the application of geometric considerations are indeed quite well satisfied for $\sqrt{s} \gtrsim 15$ GeV, while for $\sqrt{s} \lesssim 15$ GeV there are significant deviations. – Combining

¹In e^+e^- collisions, the ψ' continues to appear in VMD strength, so that its decoupling in photoproduction can also be considered as an effect of the extrapolation from highly virtual to real photons [14].

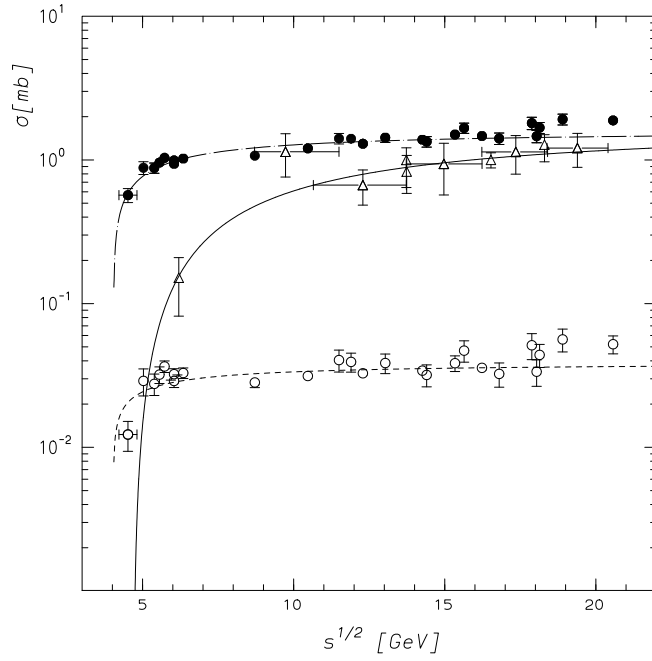


Figure 1: Cross sections for J/ψ -nucleon interactions as obtained from J/ψ and open charm photoproduction: $\sigma_{\text{el}}^{\psi N}(s)$ (open circles), $\sigma_{\text{in}}^{\psi N}(s)$ (triangles), and $(1 + \rho^2)^{1/2} \sigma_{\text{tot}}^{\psi N}(s)$ (filled circles). The lines give the results of fits (see text).

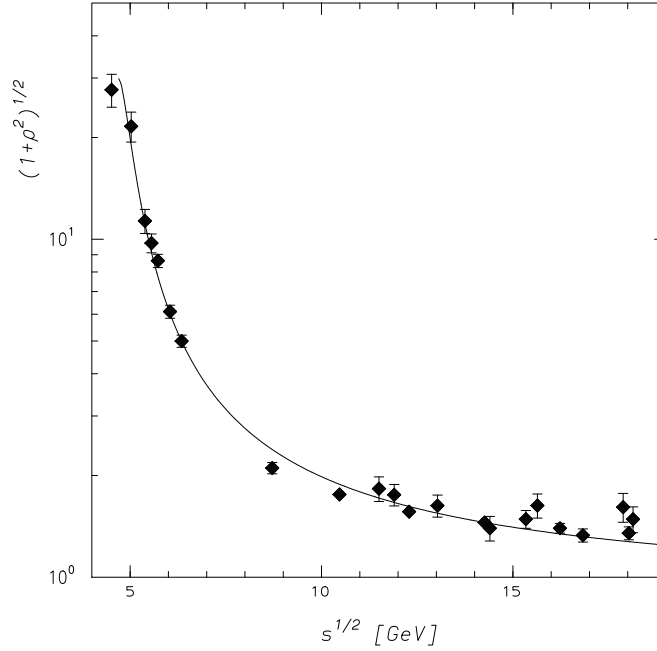


Figure 2: The data and polynomial fit to $(1 + \rho^2)^{1/2}$.

the fits of $\sigma_{\text{in}}^{\psi N}(s)$, $\sigma_{\text{el}}^{\psi N}(s)$ and $(1 + \rho^2)^{1/2}$, we obtain a fit to $(1 + \rho^2)^{1/2}\sigma_{\text{tot}}^{\psi N}(s)$ (included in Fig. 1) which is compatible with the form of Eq. (8) and the parameters given in Table 1.

σ_x	A_x	k_x	$\chi^2/\text{d.o.f.}$
σ_{in}	1.90 ± 0.35	1.93 ± 0.4	0.29
σ_{el}	0.039 ± 0.0014	0.284 ± 0.051	1.7
$\sqrt{1 + \rho^2} \sigma_{\text{tot}}$	1.90 ± 0.35	0.66 ± 0.03	3.0

Table 1: Fit parameters for $J/\psi - N$ cross sections

The quantity of particular interest for J/ψ suppression in nuclear collisions is $\sigma_{\text{in}}^{\psi N}(s)$; its energy dependence as obtained from photoproduction is shown in more detail in Fig. 3. Since we have not discussed the threshold behaviour of light quark contributions to Eq. (6), the curve of Fig. 3 represents in principle only an upper bound. However, $p-p$ data as well as perturbative studies show a strong threshold suppression also for open charm hadroproduction [17], so that $\sigma_{\text{in}}^{\psi N}(s)$ may well coincide with this upper bound.

Our considerations are based on vector meson dominance, which assumes that in J/ψ photoproduction, a $c\bar{c}$ fluctuation of a photon of momentum P is brought on-shell by interaction with the nucleon, forming a J/ψ of momentum Q . For the validity of such a picture, the longitudinal coherence length z_L of the fluctuation cannot be much smaller than the size r_N of the nucleon. Hence for

$$z_L \simeq \frac{1}{P_L - Q_L} = \frac{1}{P_L - \sqrt{P_L^2 - M_\psi^2}} \ll r_N, \quad (9)$$

vector meson dominance could break down; we should therefore limit our results to $\sqrt{s} \gtrsim 5$ GeV in the following discussion. Note that essentially the entire range shown in Fig. 3 falls into the region of VDM validity.

Any model for J/ψ -hadron interactions, whether based on short distance QCD or on hadron exchange, must satisfy the bound given in Fig's. 1 and 3. With this in mind, we now turn to the theoretical approaches to inelastic ψN interactions mentioned above.

- Short distance QCD: The heavy quark constituents and the large binding energy of the J/ψ had stimulated short distance QCD calculations quite some time ago [2, 3]; these were subsequently elaborated [4] - [6]. They are based on the gluon-dissociation of the J/ψ (the QCD photo-effect), convoluted with the gluon distribution function in the nucleon as determined in deep inelastic scattering (see Fig. 4a). The produced final state contains a $D\bar{D}$ pair and a nucleon, and the resulting form is

$$\sigma_{\text{in}}^{\psi N}(s) \simeq \sigma_{\text{in}}^{\psi N}(\infty) \left\{ \frac{(2M_D + m)^2 - M_\psi^2 - m^2}{s - M_\psi^2 - m^2} \right\}^{6.5} \quad (10)$$

where $\sigma_{\text{in}}^{\psi N}(\infty)$ denotes the high enery geometric cross section and m the nucleon mass. Eq. (10) shows a very strong damping in the threshold region. The power 6.5 of the damping factor is obtained from scaling gluon distribution functions; more realistic distributions will lead to a further damping at low and an increase at high \sqrt{s} [22].

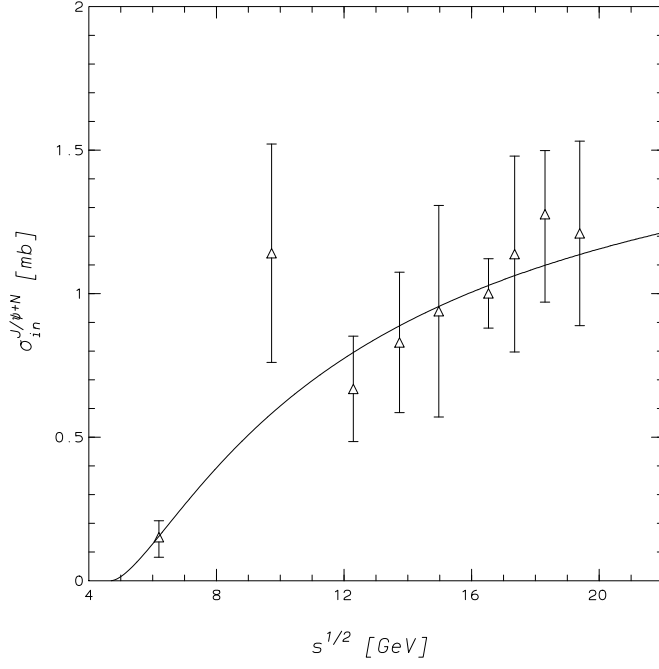


Figure 3: The inelastic $J/\psi - N$ cross section together with the fit given by Eq. (8).

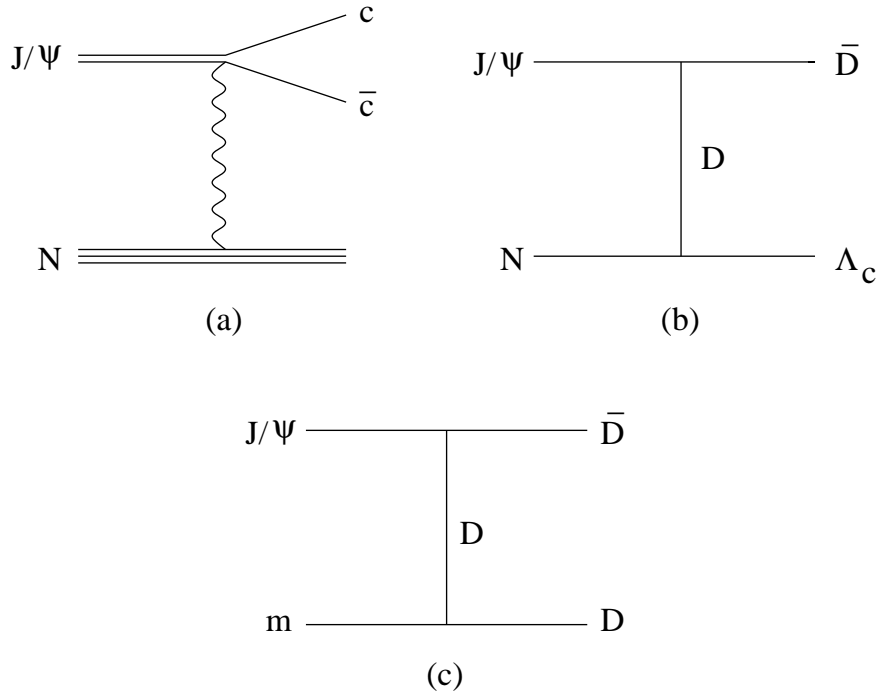


Figure 4: Schematic illustrations of J/ψ dissociation by nucleon collisions for (a) short distance QCD (b) hadron exchange, and (c) hadron exchange in meson collisions.

• Charm exchange: The interaction of a J/ψ with a meson or nucleon is here considered to take place through open charm exchange. Such a mechanism has been considered in [7] - [9] for J/ψ -meson and J/ψ -nucleon interactions; for the latter it leads to a Λ_c and a \bar{D} (see Fig. 4b), for the former to a $D\bar{D}$ final state (Fig. 4c). In the threshold region, the cross sections for meson (m) and nucleon (N) projectiles are of comparable size, as expected from the fact that the ratio of the couplings

$$g_{DN\Lambda_c}^2/g_{mD\bar{D}}^2 \quad (11)$$

is of order unity [8]. In [7, 9], no explicit results are given for the J/ψ -nucleon cross section. The values obtained there for J/ψ -meson interactions are quite similar, however, to those in [8], where the J/ψ -nucleon interaction is calculated as well. We shall therefore use this form for our actual comparison.

The short distance QCD form Eq. (10) for inelastic J/ψ -nucleon interactions, with $\sigma_{\text{in}}^{\psi N}(\infty) = 1.9 \text{ mb}$, is seen in Fig. 5 to agree quite well with the constraint from open charm photoproduction. We recall moreover that the use of more realistic parton distribution functions would further improve the agreement. In contrast, the charm exchange cross section [8] is found to overshoot the data by more than a factor two over the entire threshold region; the data point at $\sqrt{s} = 6 \text{ GeV}$ is an order of magnitude lower than the predicted value. Moreover, the predicted functional form differs from that of the data. The form shown in Fig. 5 is obtained by smoothly extrapolating the results given in [8] for $\sqrt{s} \leq 6 \text{ GeV}$ to the same geometric cross section $\sigma_{\text{in}}^{\psi N}(\infty)$ as for the short distance QCD result.

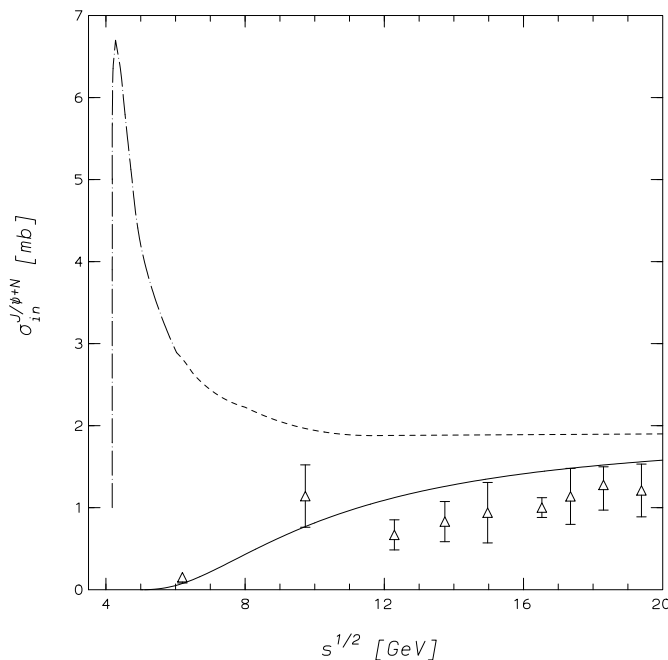


Figure 5: The inelastic $J/\psi + N$ cross section compared to the predictions of the short distance QCD [5] (full line) and the meson exchange model [8] (dashed-dotted line) extrapolated to higher energy (dashed line).

We therefore conclude that the threshold enhancement obtained in hadron exchange models for inelastic J/ψ -hadron interactions is not compatible with J/ψ and open charm photoproduction data. This excludes such mechanisms as possible source for any ‘anomalous’ J/ψ suppression observed in $Pb-Pb$ collisions at the CERN-SPS [23]. Nevertheless, it would be interesting to compare the inelastic J/ψ -nucleon cross section obtained from photoproduction to possible direct measurements using either an inverse kinematics [24] or an $\bar{p}A$ annihilation [25] experiment.

In closing, we note that in addition to these models considered here, quark interchange or rearrangement has been discussed as possible mechanism for inelastic J/ψ -hadron interactions [26, 27]. This leads to cross sections which are still much larger very close to threshold; this is a kinematic region in which VDM is not really reliable. Nevertheless, the extremely large dissociation cross section of these models corresponds to a large imaginary part of the J/ψ -hadron scattering amplitude. Dispersion relations relate its value near threshold to the real part of the amplitude over a large range of energies. This is expected to result in an elastic cross section which strongly violates the bounds shown in Fig. 1, so that also here photoproduction results will very likely prove to be incompatible also to such an approach [28].

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